Sensorimotor correlation using printed synaptic transistors and conditioning PCB

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***Abstract*— The advances in robotics are often inspired from biological systems, which have attained harmonised functionality and efficiency through billions of years of evolution. Motivated by the nature, this paper presents the realisation of sensorimotor correlation using printed synaptic transistor. While such a concept has drawn increasing attention recently, no report on the adopted technology details has been published. To this end, this paper specifically presents the technical elements for the practical realisation of the concept through printed synaptic transistor and the development of the conditioning printed circuit board (PCB) for operating the as-realised device. This work presents a possible roadmap for the future advancement towards e-Skin with neural-like processing capability through a heterogenous integration of printed circuits on flexible PCBs.**

***Keywords*— Printed electronics; sensorimotor correlation; distributed computing; synaptic transistor; electronic skin.**

I. Introduction

Next-generation of robots are expected to have human-level of perception to adapt and interact with the environment in a way similar to humans and animals [1, 2]. For this, it is imperative to have a large number of multimodal sensors to obtain rich tactile inputs, along with the capability to efficiently process the abundant data in real-time [3, 4]. This is a challenging task for most state-of-the-art robots, as several technology bottlenecks such as high-power consumption, high data latency and the lack of integrated computing resources available in the robotic platform remain unresolved [5]. Biology is the best teacher for resolving such issues. Through billions of years of evolution, various species of organisms have developed their own ways to manage the abundant sensory inputs. One common observation, from primates to low-level insects, is the development of localised sensorimotor correlation, either pre-defined (hardwired) or acquired through learning afterwards, to locally scale down the sensory input to be transmitted to the brain. For example, the human body shows the patellar reflex. This behaviour is independent of the higher level of the nervous system (e.g., brain), and is a reflection of the localised correlation between sensory input and motor output, through the low level(s) of the spinal cord [6]. Even for simple insects such as locusts, such correlations have been widely observed for grooming, gap crossing and escaping from the undesired environments [7]. Mimicking such correlations in an adaptive manner could largely reduce the cognitive load on the receiving end (*e.g.*, the robot).

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From the mechanical viewpoint, the biological sensory (e.g., skin) and motor (e.g., muscles) organs are soft, flexible, stretchable and self-healable (in many cases) [8-11]. Such a mechanical nature allows these organs to cover the whole body, and effectively interact with external environments. Similar requirements are expected for the next generation of robots too. The development of sensors integrated spatially on the soft substrates have fostered the development of e-skin [12-16]. In the meantime, the research on responsive hydrogels, shape memory, etc, has been used as the actuation manner for soft robots [17-18]. Developing the adaptive correlation between them, all on the soft platform, in a similar manner as the human body does, is of great interest. However, realising such functionalities (adaptive correlation) requires the use of neuromorphic hardware, especially those that can function as synapses. This is complicated and resource consuming in Si based CMOS [19]. The challenges are greater because the development of soft electronics is far behind the conventional rigid Si based CMOS and most of the reported work in soft electronics have demonstrated limited number of transistors (tens to hundreds) [20-22]. As such, mimicking the biological synapse function in a concise and efficient manner is important for the overall realisation of the proposed functionality.

Several works have been carried out to realise the above-described concept using emerging synaptic devices [23-25]. For example, we have demonstrated the “in-skin” learning of the pain-like reflex using printed ZnO nanowires (NWs) based synaptic transistors. While our previous paper has mainly focused on the scientific aspects (e.g., device physics, hardware neuropathway demonstration along with associative learning and the theory of use and disuse, etc) [25], the technological details such as the arrangement of the conditioning circuit, especially in a PCB manner and the fabrication of the synaptic transistors were not reported in detail. For better reproducing of our results, herein we present these technical details for the realisation of the adaptive sensory-motor correlation. Whilst the synaptic transistor is obtained by contact printing, the presented PCB is still in the rigid form factor. In the future, the whole system can be made flexible by using a flexible PCB and flexible synaptic device, wired by printed interconnects. We believe, this paper complements our previous work, and together they pave the way for the development of next-generation of smart electronic skin (e-Skin) based neurorobots, and neural interface.

This paper is organised as follows: Section II discusses the fabrication of the synaptic transistor using the contact printing method, and the possibility to realise such devices in a dense manner on the soft substrates; Section III discusses the synaptic behaviour of the fabricated device and the PCB for the overall

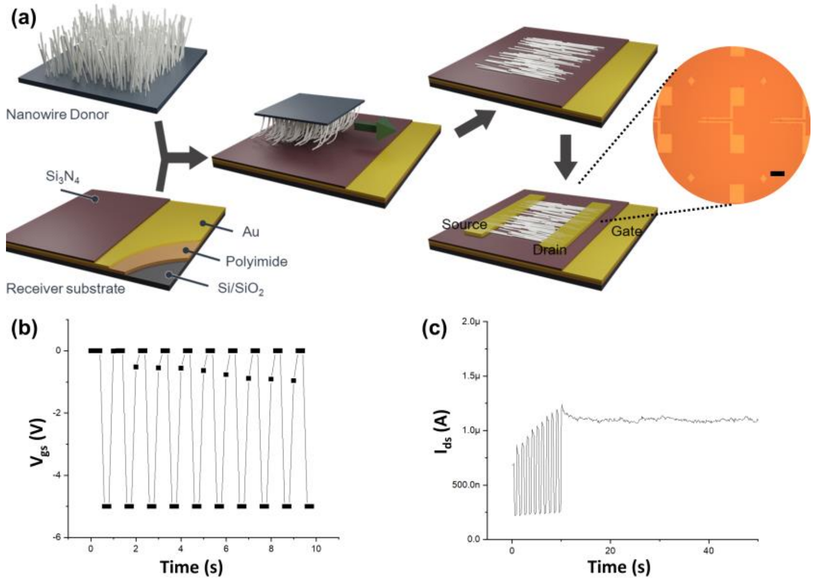

Figure **1.** (a) Fabrication process flow for realising flexible synaptic transistor using printing ZnO NWs. The scale bar is 100 μm. (b) Pulse voltage stimuli applied to the gate terminal. (c) The corresponding synaptic behaviour reflected in the drain-to-source current.

control circuits. The key outcomes are summarised in Section IV.

II. Fabrication of Synaptic Transistors using Contact Printing Method

The synaptic transistor is realised by printing ZnO NWs from the donor substrate to the receiver substrate, followed by standard lithography process to define the source and drain contacts. Fig. 1 describes the fabrication process for the device. Importantly, the synthesis of ZnO NWs was carried out using commercial Au nanoparticles with precisely defined dimensions (diameter of 80 nm), using the chemical vapour transport method. The synthesis temperature was set at 880°C. Under a higher synthesis temperature, the synthesised products show a significant portion of ZnO flakes mixing with the NWs, which leads to drastic non-uniformity from the material point of view. Whereas using a synthesis temperature below 860°C leads to a significant decrease in the density of the grown NWs. The reaction temperature at 880°C provides an optimised condition with a sufficient growth rate and acceptably low density of the ZnO flakes. The as synthesised NWs were printed onto receiver substrate using a customer-built contact printing setup reported elsewhere [26-27]. The self-aligned, automated setup minimises the location-to-location and batch-to-batch non-uniformity in the printed NWs and holds a great promise for the development of highly uniform, large-area electronics using printed NWs. The synaptic behaviour of the as-fabricated device has been thoroughly explained in the previous work [25]. Nevertheless, for the sake of completion, the test showing the synaptic behaviour of the transistor is shown in Fig. 1b and 1c. This is the foundation for the later realisation of the “bio-like” learning behaviour using the conditioning circuit.

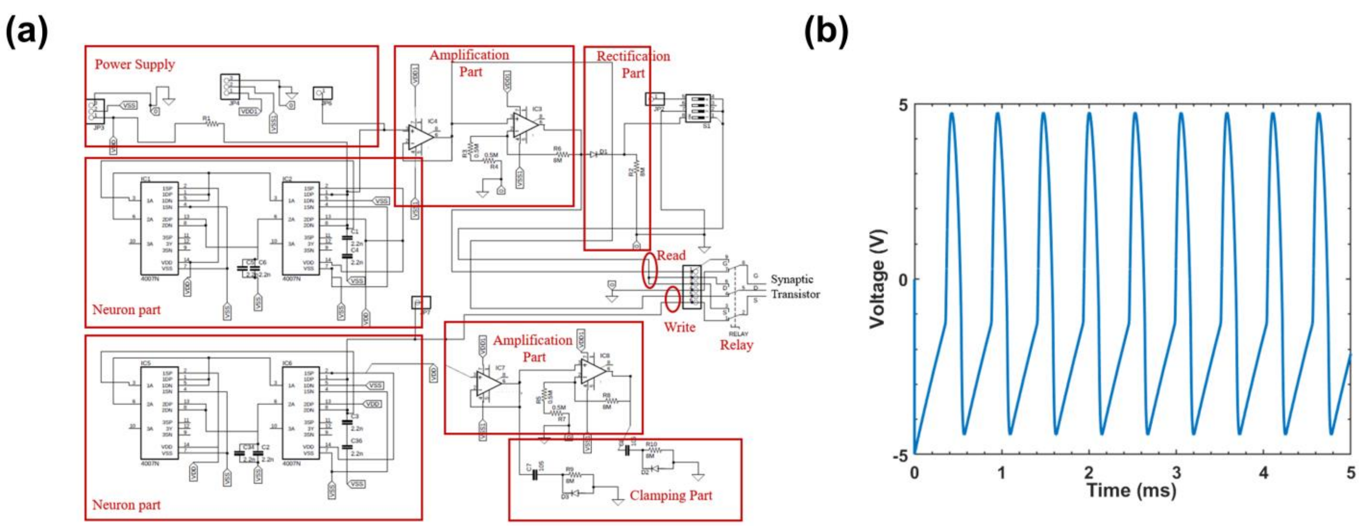

Figure **2.** (a) The detailed circuit diagram. (b) The SPICE simulation of a discrete neuron.

III. The Condiitoning Circuit for Synaptic Transistor Operation in a Bio-like Manner

A. The overall working schema

The demonstration of bio-like learning is achieved by the association of the sensory input with the motor output, through the synaptic device. Specifically, this requires a block to provide the sensory input and a block for the motor output, both in a neuromorphic manner. The working diagram can be found in our previous paper [25]. In this paper, we focus on the actual implementation (*i.e.*, circuit diagram) of the whole conditioning circuit.

B. The circuit diagram and working principles

The core part of the conditioning system is the neuron circuit. For this, we adopted the design reported in [28]. The IC CD4007 was utilised wherein its dual complementary nature was exploited to design a discrete neuron. Such a neuron circuit could output spiking signals under external synaptic current stimuli following biological encoding principles, *e.g.*, rate encoding. The simulation of the discrete neuron is carried out in LTspice utilising the SPICE CD4007 library with a user-editable BSIM4 model describing the transfer characteristics of the transistors. The simulation results are shown in Fig. 2b wherein the rising and falling slopes of the spike are controlled via both the parasitic capacitance of the discrete devices as well as the charging and discharging capacitors. Nevertheless, such a signal may not be enough for efficiently training of the synaptic device, and therefore the amplification was added. Specifically, the OPA551 IC has been utilised both as a dual-supply amplifier and buffer, along with two resistors of 1 MΩ and 8 MΩ, respectively, leading to a net 8-fold amplification. Such an extra step could be potentially eliminated by engineering the synaptic device. This will be explored in the future. The amplified signal is fed to the gate of the synaptic transistor as one of the training signals. In the meantime, the spiking signal from the motor neuron is fed back into the source and drain terminals of the synaptic transistor. Similarly, the spiking signal fed back for training has been modified with a clamping circuit (see clamping part of Fig.2) and an amplification circuit (see amplification part of Fig. 2), for better training of the synaptic device. To initiate the desired behaviour (*i.e.*, the sensorimotor correlation) via the synaptic transistor, an external teacher signal is needed. For this, a rectification circuit (rectification part of Fig.2) is used to provide the desired spiking signals. It should be noted that the teacher signal is only to initiate the desired correlation. After teaching, the system can sustain the taught pattern by itself, if practised regularly (otherwise it will forget just like we humans do): this is similar to the theory of use and disuse in biology. If the behaviour has not been taught, or a proper pathway has not been formed, even with numerous practices, the sensorimotor correlation cannot initiate by itself [25]. Here, such a correlation could enable the “pain-like” reflex and can find applications in human-robot interaction.

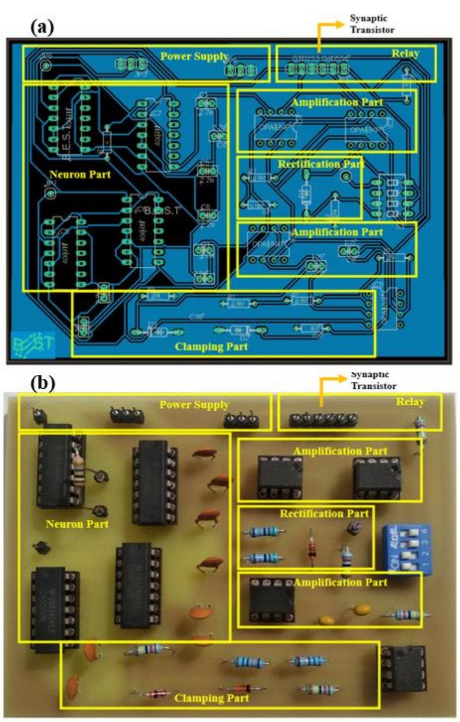

Figure **3.** Single sided through-hole component-based PCB: (a) layout, and (b) fabrication

C. Read/Write Switch

The system continuously shifts between the read and the write state. In neuroscience terms, this is equivalent to realising the functionality of synaptic efficacy and synaptic plasticity. The switching was carried out by an optical 4 channel DC 5V relay module, where three channels are used for the gate, drain, and source terminal of the synaptic transistor. The detailed connection of the circuit signal to the relay module has been provided in Fig. 2. Such an arrangement could allow the developed system to fully mimic the functionality of the biological nervous system. Moreover, for the learning of the synaptic device, the signal fed-back from the motor neuron needs to be adjusted in the time domain according to the switching scheme [25].

D. The layout for the PCB and its fabrication

The layout and the fabricated PCB for the above-described system are presented in Fig. 3 (a), and (b). The functionality of each subsection has been marked and correlated with the circuit diagram for an easier understanding. Whilst it is currently on rigid FR4 substrate, it is possible to realise an all-flexible system using a flexible PCB and flexible synaptic device, interconnected by printed metallic ink as shown in some of our previous works [29-32].

IV. Conclusion

In conclusion, we have presented the technical details for the realisation of sensorimotor correlation using synaptic transistor and the conditioning circuits in a single PCB. The developed behaviour shows a great promise in scaling down the cognitive load for the brain, as both the sensory data and the neuron output has been processed locally in a neuromorphic manner just as our human body does. This aspect is particularly important when the sensory inputs and the neuron outputs upscale for achieving human-level tactile sensation, perception and response of the smart robots. Going forward, we aim to realise a fully flexible and printed systems using the details discussed in this paper.

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